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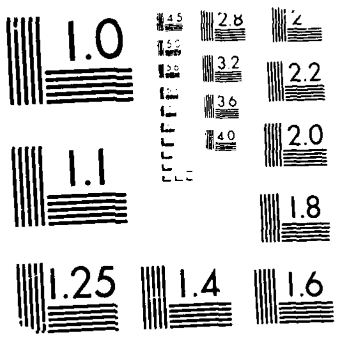
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SELECTIVE MECHANISMS IN AUDITORY AND BIMODAL SIGNAL PROCESSING

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SELECTIVE MECHANISMS IN AUDITORY AND BIMODAL SIGNAL PROCESSING

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A-1

I. INTRODUCTION

The purpose of this research program was the investigation of mechanisms of attention in auditory and bimodal information processing. The manner in which division of attention influences three stages of information processing -- stimulus coding, decision making, and response selection -- was described previously by the principle investigator in a general, quantitative theory of attention (Shaw, 1980, 1982). Previous work had shown that, within the framework of this theory, the effects of division of attention on the first two stages could be separately identified. As in the earlier research, the work reported here has focused on two key issues: (1) What are the decision processes involved in combining information from two or more sources, and (2) Does division of attention degrade the information obtained from each source (i.e., does it result in losses of information at the coding stage)?

An extensive five-year research program was planned to continue work begun under the previous grant (AFOSR-81-0215). Funding for the current grant began in July, 1983, and some research continued while, at the same time, considerable effort was devoted to upgrading our laboratory computer system from PCs to a more powerful mini-computer. However, due to the untimely death of the Principle Investigator, Dr. Marilyn L. Shaw, in November, 1983, only a small fraction of the proposed work was actually completed.

In January, 1984, Drs. Kowler and Sternberg were approved as acting PIs. It was decided that ongoing experiments and necessary follow-up experiments would be completed in a timely fashion, and no additional work would be started. Dr. Robert Mulligan, Research Associate on the grant, continued collecting data on a series of auditory decision experiments until August, 1984, at which time he assumed a full time job in industry. At that time, an extension was granted so that data analysis and writing could continue. Work continued on a series of visual attention experiments under the supervision of Dr. Sternberg at Bell Laboratories until January, 1985. After being granted an extension of time with no additional funds, a final series of follow-up experiments continued in Dr. Sternberg's lab at the University of Pennsylvania during 1985-1987.

II. DISCUSSION OF FINDINGS

Three sets of experiments were carried out under support of this grant. The first involved further investigations of combining information from multiple sources of auditory information (following up work from the previous grant). The second line of research examined the effects of stimulus complexity (in terms of "texton" differences described by Julesz, 1982), on divided attention decrements in a visual attention task. The final series of experiments followed up earlier work by Dr. Shaw on dividing attention among spatial locations where luminance increment stimuli might occur. Each of these lines of research will be described below.

A. Integration of Auditory Information

In previous work, Shaw (1982) explored how subjects combine multiple sources of information to make a "yes-no" decision. This question was examined in the context of a general information processing model comprising sensory coding, decision and response stages. Our work focused on the effects of dividing attention on the first two stages: (1) the *sensory coding stage*, in which stimulus energy is transformed into some internal representation, and (2) the *decision stage*, in which these internal representations are used to determine a response.

The output of the coding stage is conceived as an index, for each stimulus source, of the strength of the signal at that source. The signal strength measure for source i will be denoted as X_i. The actual stimulus dimension these strength measures represent differs for different tasks and stimuli. For the auditory signal detection tasks described in this section, the indices are the amount of energy or signal-to noise ratio in auditory channels.

In the second stage, decision making, these strengths are evaluated according to some decision rule. In the auditory detection tasks the decision is between two choices -- signal present or absent.

Given this general framework, the question we have addressed is the following: When a signal is possible at any of two or more sources, how are the strength measures from these sources pooled to arrive at a binary decision ("yes", a signal was presented in at least one channel or "no", no signal was present)? Several alternative hypotheses have been proposed to answer this question. The two major classes of models that have been considered are the *Integration Models* and *Independent Decisions Models*. These classes of models, among others, are presented in detail in Shaw (1982). The Independent Decisions (ID) and Integration (INT) models will be described briefly below, in terms of the auditory detection experiments to be reported. In this description, sources of information are defined as frequency channels in the auditory system.

A few words about auditory channels before describing the models. The choice of frequency channels as information sources implies a widely held model of auditory information processing. In this model, the detection of pure tones is mediated by a pitch coding mechanism, the first stage of which is conceived as a series of bandpass filters. The conception of these filters is based on the notion of a *Critical Band* -- that is, the limited band of frequencies around a pure tone which are effective in masking the tone. Data from masking studies show that noise at frequencies outside of the Critical Bandwidth (CBW) has no significant effect on detection of a tone at the center of the band. Non-overlapping auditory filters or Critical Bands, then, can be thought of as independent channels or sources of information -- independent at least in the sense that noise in non-overlapping channels is uncorrelated.

1. The Models. The ID and INT models are schematized in Figure 1. The top half of the figure shows a general version of the Integration model (also called the Linear Combination Rule). In this model, outputs of the two independent frequency channels -- the strength measures X_a and X_b are summed to arrive at the decision variable Y. This pooled strength measure (Y) is then evaluated against a criterion to determine the appropriate response -- "Yes", if Y exceeds the criterion or "No" if it does not.

According to the Independent Decisions model (bottom half of the figure), separate, tone-present absent decisions are made for the strength measures associated with each channel. In a subsequent part of the decision stage, the results of these binary categorizations are pooled and compared to a criterion to arrive at a response. In our experiments, as is often the case, the criterion number of "signal present" decisions is set to "1", that is, subjects are instructed to say "yes" if they detect ***either*** signal.

The essential difference between the models lies in how the stimulus information in the strength measures (X_a and X_b) is combined in determining whether or not a signal has occurred in either channel. In the INT model the ***raw*** strength measures are summed whereas in the ID model, separate binary decisions based on the strength measures are summed.

2. Previous Work and Rationale for the Present Studies. Until fairly recently, predictions of these models were always expressed in terms of different response measures -- d' for the INT model and probability correct for ID. Shaw (1980) developed expressions of the models in terms of the same constraints on the same set of response measures. This development allowed the models to be compared more directly. In several sets of experiments that followed, Shaw and her collaborators found that the class of ID models accounted for the data quite well for nearly every subject in nearly every situation studied.

Summarized in Table 1, these studies included combining information from spatial locations at which luminance increments or letter stimuli were presented, combining information from auditory and visual modalities, and from different visual spatial frequency channels.

A major goal of the research reported here was to extend this series of studies to see how information from separate auditory frequency channels is combined. Given the consistent evidence for ID with other types of stimuli, it was expected that ID would best explain the auditory data as well. However, a review of the auditory signal detection literature led to the opposite expectation. Data from several experiments carried out in the 1950's and 1960's were interpreted as supporting the INT model (e.g. Marill, 1956, Green, 1958). In some of these

studies, however, no ID model was tested, and in others, the level of performance was not optimal for discriminating the models.[1]

In an attempt to resolve the discrepancy between our expectations and the evidence from the literature, we ran two experiments under support of the previous grant (AF81-0215). The experiments employed the same two-signal paradigm we had used in previous studies in other stimulus domains (see Figure 2). The two possible auditory signal frequencies -- call them tones A and B -- were equiprobable, and the occurrence of A on a trial was statistically independent of the occurrence of B. The resulting four possible stimuli were tone A, tone B, the complex tone A+B, and neither tone (noise only). One of these four was presented on each trial.

Subjects were instructed to divide their attention equally between the two tones. Their task was to respond "yes" if they detected either tone (or both) and "no" if they heard neither tone. The stimuli consisted of digitally synthesized sine waves, mixed with analog, band-limited white noise. Signal generation, timing, and response collection were controlled by custom-built hardware interfaced to an Apple II microcomputer.

The sequence of trial events was as follows: Each trial began with a visual warning signal followed by the observation interval during which one of the four stimuli was presented. At the end of the observation interval, a response prompt appeared on the subject's monitor, and he or she made his or her response. Subjects were then given feedback telling them which stimulus had been presented. Subjects were practiced, first in a simple single-tone signal detection task and then in the two-signal paradigm, for a total of eight or nine sessions. Data were collected in 12 subsequent sessions, each consisting of four blocks of 25 trials.

The data were compared to predictions of the two models using Shaw's (1980) analysis. The results showed clearly that information about the presence absence of tone signals in two distinct frequency channels is combined according to the ID model. This was true both when the two tones were separated by a Critical Bandwidth (CBW) or more and when the tones were within the same Critical Band. Combining the data from both experiments, the ID model was supported in 31 of 36 cases. Contrary to our expectations, and to previous findings, the INT model did not receive convincing support when the pair of stimulus tones were within a CBW of one another. Only when the signal frequencies were very close together (.05 CBW) was there some evidence for the INT model. These data are presented in greater detail in Appendix 1.

The discrepancy between our results and those of previous studies, especially in the within CBW conditions, was puzzling. Looking back at those earlier studies, however, a potentially important difference between the experimental paradigms was discovered. In the earlier studies by Marill (1956) and Green (1958), tone A, tone B, and the AB complex tone were presented in separate blocks of trials. In the independent, two-signal paradigm used in our experiments, the different stimuli were mixed within the same block of trials. Note that in the independent, two signal design (referred to as the *Mixed* design below), the presence absence of a signal in one channel cannot be predicted on the basis of information about the presence absence of a signal in the other channel. This is not the case in the *Blocked* design used in the earlier studies, in which signals in the two channels are completely correlated. In the experiments described below, performance in the Mixed and Blocked paradigms were compared within the same study to examine their influence on how information from two tone stimuli are combined in a detection task.

It should be made clear that it is not simply a methodological question that is being addressed. A more interesting theoretical issue is also at stake -- namely, that the decision rule for

1 Although the ID and INT models [illegible] distinct, their predicted performance values, in many circumstances, differ by very little. [illegible] are carefully chosen, however, they can be successfully distinguished with a reasonable [illegible]

combining information from two sources is not fixed, but may instead be flexible, shifting from ID to INT according to the context (Blocked vs. Mixed designs) in which the signals are presented.

3. Experiment 1. The first experiment was designed to test the hypothesis that the decision rule for combining two tones would differ for different presentation conditions -- INT rule with the Blocked design and ID rule with the Mixed Design. Comparison of performance in the two paradigms was complicated by the fact that predictions of the models have traditionally been expressed in terms of different response measures -- percent correct for ID and d' for INT. One advantage of the analysis developed by Shaw (1980, 1982) is that it allows comparison of the models in terms of the same response measure. However, since Shaw's analysis assumes that observers are dividing their attention between two statistically independent signal sources on all trials, is is not applicable to data from the blocked design. Another type of analysis was required, one in which predictions of both models were expressed in common terms. Our first step, then, was to develop these predictions, and to determine whether they could be used to successfully discriminate between the models. This task was accomplished by deriving predictions for both models in terms of the probability of a "yes" response to the complex tone stimulus (A+B). These predictions required an additional assumption not necessary in the independent paradigm; namely, that dividing attention between two frequency channels does not diminish the information obtained from each. This assumption is substantiated in the literature and by data from our lab.

a. Procedure. In this first study, subjects were run in the Mixed and Blocked conditions on alternate days. The procedure in the Mixed sessions was the same as that used in our earlier auditory detection studies in the two signal, independent paradigm. All four stimulus types (tone A, tone B, tones A+B, and noise only) were mixed within each block of trials. A session consisted of four blocks of 120 trials.

In the Blocked or correlated sessions, subjects were again run in 4 blocks of 120 trials per session, but each block contained only one signal type mixed with noise only trials. Thus, a session comprised 1 A, 1 B, and 2 A+B blocks.

The signal frequencies used were 700 and 1200 Hz. Stimulus tones were 120 msec. in duration. The sequence of trial events consisted of a warning signal followed by an observation interval during which a signal or noise stimulus was presented. This was followed by a response interval during which subjects made their "yes no" response and visual feedback showing which stimulus had been presented.

Four subjects received extensive practice in each condition, and then participated in eight data collection sessions.

b. Results. The data, expressed in terms of the probability of a "yes" response to each stimulus type, were compared to the predictions of the ID and INT models. The results are plotted in Figure 3. The figure shows observed and predicted probability of a "yes" response to the compound tone (A+B). The data have been normalized such that the ID model prediction is Pr{yes} = 0 and the INT model prediction Pr{yes} = 1.0. The actual difference between the two predictions in terms of Signal Detection Theory is approximately half a d' unit. Looking at the data from the Mixed condition (circles in the figure), it can be seen that all four subjects conformed to the prediction of the ID model and rejected the INT model. This result replicated our previous findings for various stimulus types in the two signal, independent paradigm.

For two of the subjects (JS and LP), introduction of the Blocked or correlated condition on alternate days succeeded in altering the decision rule. For these two subjects, the INT model was clearly favored over ID. Of the two remaining subjects, one apparently continued to use an ID rule for combining information from the two signal frequencies (SO), data from the other subject (RP) fell between predictions of the two models, rejecting neither

These results provided some evidence for our hypothesis that the decision rule in this type of task may shift as a function of stimulus presentation conditions (specifically, depending on whether the occurrence of tones in the two channels is independent or correlated). But why did only two of the subjects show this clear shift? It was suspected that the failure to observe a shift of decision rules on the part of the other two subjects might have been due to the day-to-day alternation of conditions. Perhaps for these subjects, a shift in decision strategy requires more than one consecutive session in the new condition. This concern was addressed in the next experiment by collecting data in each condition for four consecutive sessions.

4. Experiment 2. Five new subjects were recruited for the second experiment. They were first practiced for six sessions exclusively in the Blocked condition. The practice was followed by four Blocked data collection sessions.

Data from the Blocked condition for the five subjects are shown as the open circles in Figure 4. For two of the five subjects (JP & SC), the INT model was clearly favored. Data from the other three subjects rejected both models (or neither, depending on which alpha level one chooses for the significance test).

Ideally, we would have continued collecting data in the Blocked condition to see if these three subjects would move closer to the prediction of the INT model with more experience in this condition. Because of time constraints, however, all subjects were switched to the Mixed (Independent) condition at this point. Four sessions of practice were followed by four data collection sessions. Data from the Mixed condition are shown as the filled circles in Figure 4. The data points for all five subjects moved in the direction of the prediction of the ID model. For four of the five, the ID model was uniquely supported.

For two subjects who were able to continue in the experiment, an ABBA sequence was completed by collecting another four sessions of Mixed data followed by a final four sessions of Blocked data. Data from these sessions, shown as open and filled squares in Figure 5, were very close to the first set of data from each condition. The important result is that, when shifted back to the Blocked condition, both subjects shifted significantly toward the prediction of the INT model.

5. Discussion. While the results of these auditory detection experiments are not completely consistent across subjects, they do allow us to draw some tentative conclusions. The results and our conclusions are summarized below.

First, confirming our previous findings, we found that for auditory sources defined by non-overlapping frequency channels, when signals are presented in a Mixed design (the two-signal, independent paradigm), the data overwhelmingly support the ID model. Secondly, we found, in agreement with earlier experiments from other labs, that the ID rule is not always used. When the tone stimuli are presented in a Blocked or correlated fashion, data from all subjects were fit as well or better by the INT model as they were by the ID model.

The importance of this result is that it implies the notion of decision *strategies*, i.e., that the decision rule is not fixed, but rather that subjects have some control over the combination rule invoked in a particular situation. Based on these results, we suggest that the rule used by a subject to make a decision about the presence or absence of a particular signal depends on the context (the set of experimental trials) in which it is embedded.

It is interesting to note that our subjects' choice of decision strategies in different conditions could be described as a tendency to optimize performance. By applying a likelihood ratio rule to the Mixed and Blocked conditions, one can predict optimum performance levels under each condition. Having done this, we found that the ID rule yields very nearly optimal results in the Mixed condition, and an integration strategy (the INT rule) yields performance nearer to optimal when information sources are highly correlated as in the Blocked condition. However, performance is not always optimal, and some subjects are better than others at selecting the best decision rule for a given set of conditions. An interesting question raised by [illegible] studies is how to train individuals to adopt the best decision rule for a given situation.

The tendency of subjects to alter their decision strategy to suit the degree of independence of stimulus sources parallels results from a set of experiments on cognitive decision making by Shaw, Bousquet & Cantor[2]. In one of their tasks, subjects were given two pieces of information about the likelihood of two horses winning two different races. They were asked to decide whether or not to bet that at least one of the two horses would win its race -- a binary decision task. When the likelihood of one horse winning was completely independent of the other horse's performance, subjects tended to make their decisions according to an ID rule. However, then performance of the two horses was highly correlated, subjects switched to an INT rule.

The switch of decision strategy in the overt, cognitive decision making task seems less surprising than the comparable result in the psychophysical tasks reported above. The interesting result from our auditory detection studies is that the same type of strategy switching or optimization behavior that subjects employ on the overt task is also seen in the psychophysical task, where the decision process has traditionally been regarded as fixed or inflexible.

B. Studies of Divided Attention as a Function of Visual Stimulus Complexity

A common finding in the attention literature is that increasing the number of sources of information among which attention is divided lowers performance (detection, identification, localization tasks) with respect to each individual source. Shaw developed a theoretical framework in which the the effects of dividing attention on the stimulus coding and decision stages of information processing could be separately assessed (Shaw, 1984, Mulligan & Shaw, 1981). In a series of experiments, Shaw (1984) examined the effects of dividing attention among spatial locations in a visual display, for both letter and luminance increment stimuli. Results of these studies indicated that, when the task required detection of simple luminance stimuli, division of attention did not cause losses of information in the stimulus coding stage. When subjects were required to give the location of a target letter among distractors, however, there was strong evidence for losses of information in the coding stage as the number of attended locations was increased.

Work by Julesz (1982) suggested that the divided attention decrement with letter stimuli may be due to the particular set of target and distractor letters chosen. According to Julesz' "texton" theory, if there is a texton difference between target and distractor, this difference will be recognized pre-attentively, and therefore, no divided attention decrement should be observed. If, however, target and distractor stimuli are equally complex in terms of their texton elements, focused attentional effort will be required to discriminate them, and therefore, a divided attention decrement would be observed.

Two experiments were undertaken to explore this hypothesis. Due to a number of complications in the methodology (including a confounding influence of apparent size differences in stimulus characters), the results of these studies were inconclusive.

C. Studies of attentional effects on the speed of detecting luminance increments

We have attempted to discriminate experimentally between two alternative theories of visual attention, as applied to the relation between the speed with which human observers detect a suprathreshold luminance increment and the frequency with which it appears at a specified location. According to one theory, visual attention is a limited capacity mechanism which affects reaction time for luminance increments by distributing limited processing resources over the visual field. The greater speed associated with higher-frequency locations would then result from the assignment of more resources to these locations. According to a competing theory, visual attention is the independent setting of distinct decision criteria for different locations

2 Unpublished manuscript, 1985

The greater speed associated with higher-frequency locations would then result from the assignment of lower criteria (less evidence required) to these locations. We conducted four reaction time (RT) experiments that were aimed at selecting one of these theories. The first three experiments are concerned with the relationship of stimulus intensity to visual attention. In two experiments with important implications, Hughes (1984) had found that intensity and signal probability have additive effects on RT. We corrected a flaw in the design of those experiments, and found a highly reliable interaction between intensity and signal probability. This finding supports the view that attention acts early in the sequence of processing operations between signal and response, where limitations on processing resources might be expected to show themselves. In the second and fourth experiments, we developed an approach to manipulating the signal frequencies at two locations that overcomes a problematic confounding of these two frequencies in past experiments. We found support for the limited capacity models for these RT tasks with suprathreshold stimuli, in contrast with conclusions from studies of the detection of threshold-level luminance increments.

A manuscript is nearing completion.

IV. PUBLICATIONS AND MANUSCRIPTS

1. Shaw, M. L. Division of attention among spatial locations: A fundamental difference between detection of letters and detection of luminance increments. In H. Bouma & D. G Bouwhuis (Eds.), *Attention & Performance X*, 109-121, Hillsdale, NJ.: Erlbaum, 1984.
2. Mulligan, R. M. & Shaw, M. L. Information Integration in Auditory Detection. Manuscript in preparation.
3. Backus, B. & Sternberg, S. Effects of attention on the speed of detecting luminance increments. Manuscript in preparation.

V. PROFESSIONAL PERSONNEL

1. Dr. Marilyn L. Shaw, Principle Investigator (died 11 83)
2. Dr. Robert M. Mulligan, Research Associate
3. Dr. Eileen Kowler, Acting Co-PI
4. Dr. Saul Sternberg, Acting Co-PI
5. Mr. Benjamin Backus, Graduate Student

VI. PAPERS PRESENTED

1. Shaw, M. L. Division of attention among spatial locations. A fundamental difference between detection of letters and detection of luminance increments. Attention & Performance X, Venlo, The Netherlands, July, 1982.
2. Mulligan, R. M. & Shaw, M. L. Dividing Attention Among Auditory Frequency Channels. Annual meeting of the Psychonomic Society, San Diego, November 1983.
3. Mulligan, R. M. Dividing Attention among Auditory Sources. Review of AF Sponsored Research, Sarasota, FL, May, 1984.

TABLE 1. RESULTS OF SEVERAL STUDIES TESTING ID AND INT MODELS

Summary of Decision Rule Studies

SOURCES	STIMULI	RESULT
Spatial Locations	Luminance Increments	ID
SHAW (1984)		
Spatial Locations	Letters	ID
SHAW (1984)		
Modalities (Aud & Vis)	Luminance Increments & Tone Bursts	ID
MULLIGAN & SHAW (1980)		
Visual Spatial Freq. Channels	Gratings	ID
YAGER, KRAMER, SHAW & GRAHAM (1983)		
Auditory Freq. Channels	Pure Tones	??

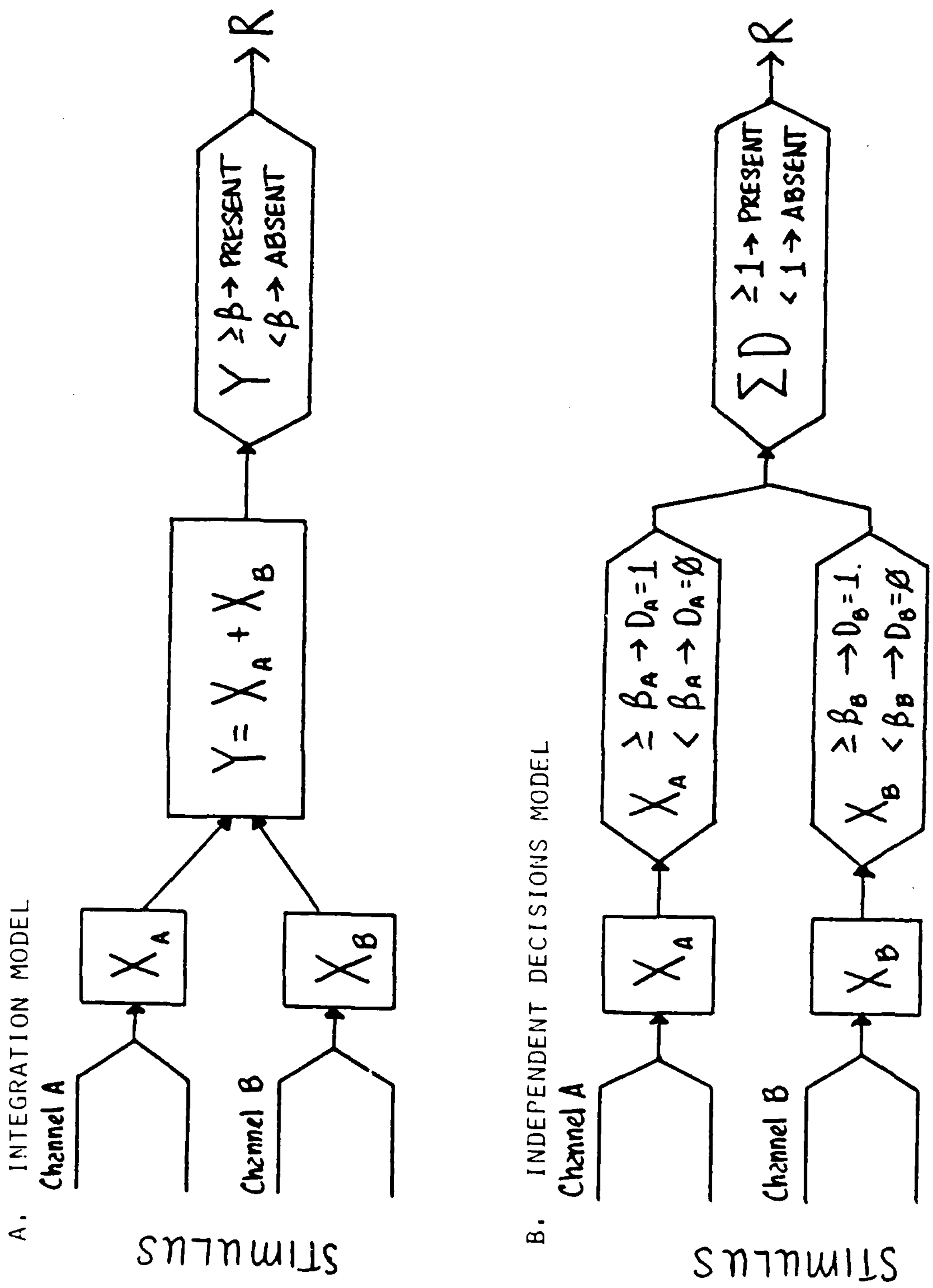

FIGURE 1. SCHEMATIC DEPICTION OF INTEGRATION (A.) AND INDEPENDENT DECISIONS (B.) MODELS.

Experimental Paradigm

- Tones A and B are Statistically Independent
- P(Tone A) = P(Tone B) = 0.5
- Stimuli

  1. Noise + Tone A
  2. Noise + Tone B
  3. Noise + Tone A + Tone B
  4. Noise only

- Response

  - "Yes" - A or B present
  - "No" - Both absent

FIGURE 2. TWO-SIGNAL PARADIGM FOR TONE DETECTION EXPERIMENTS.

Experiment 1 -- Data

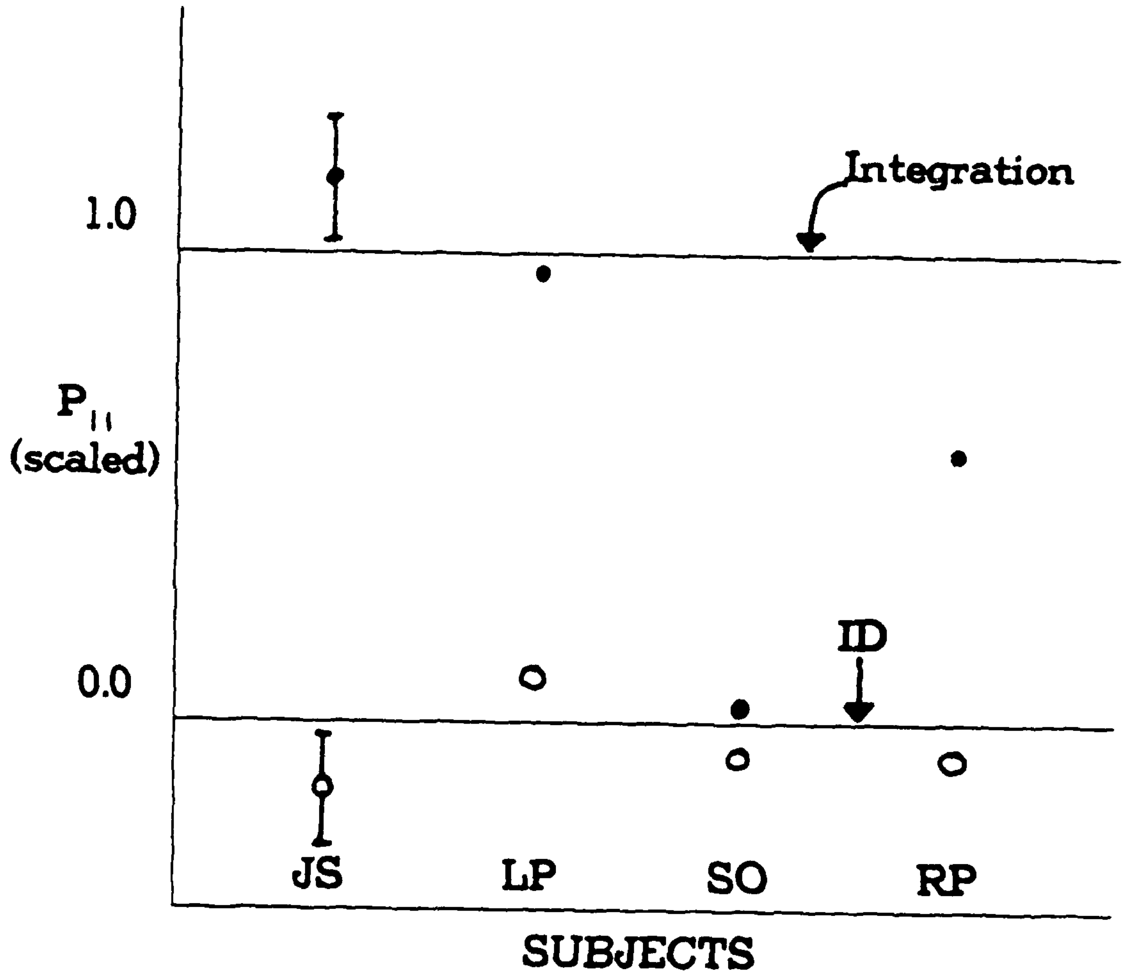

FIGURE 3. DATA FROM EXPERIMENT 1. NORMALIZED PROBABILITY OF A "YES" RESPONSE RELATIVE TO PREDICITONS OF THE TWO MODELS.

Experiment 2 -- Data

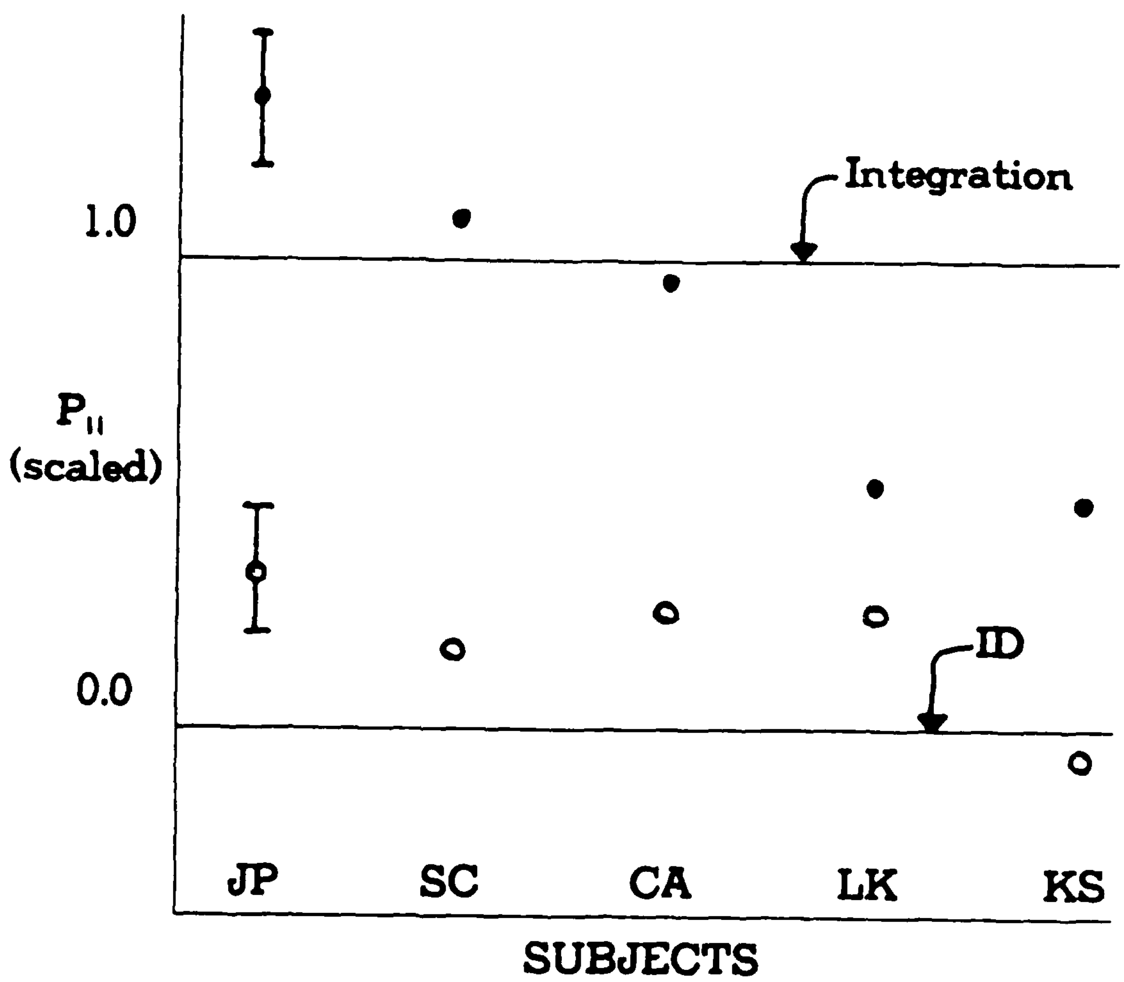

FIGURE 4. DATA FROM EXPERIMENT 2, FIRST REPLICATION.

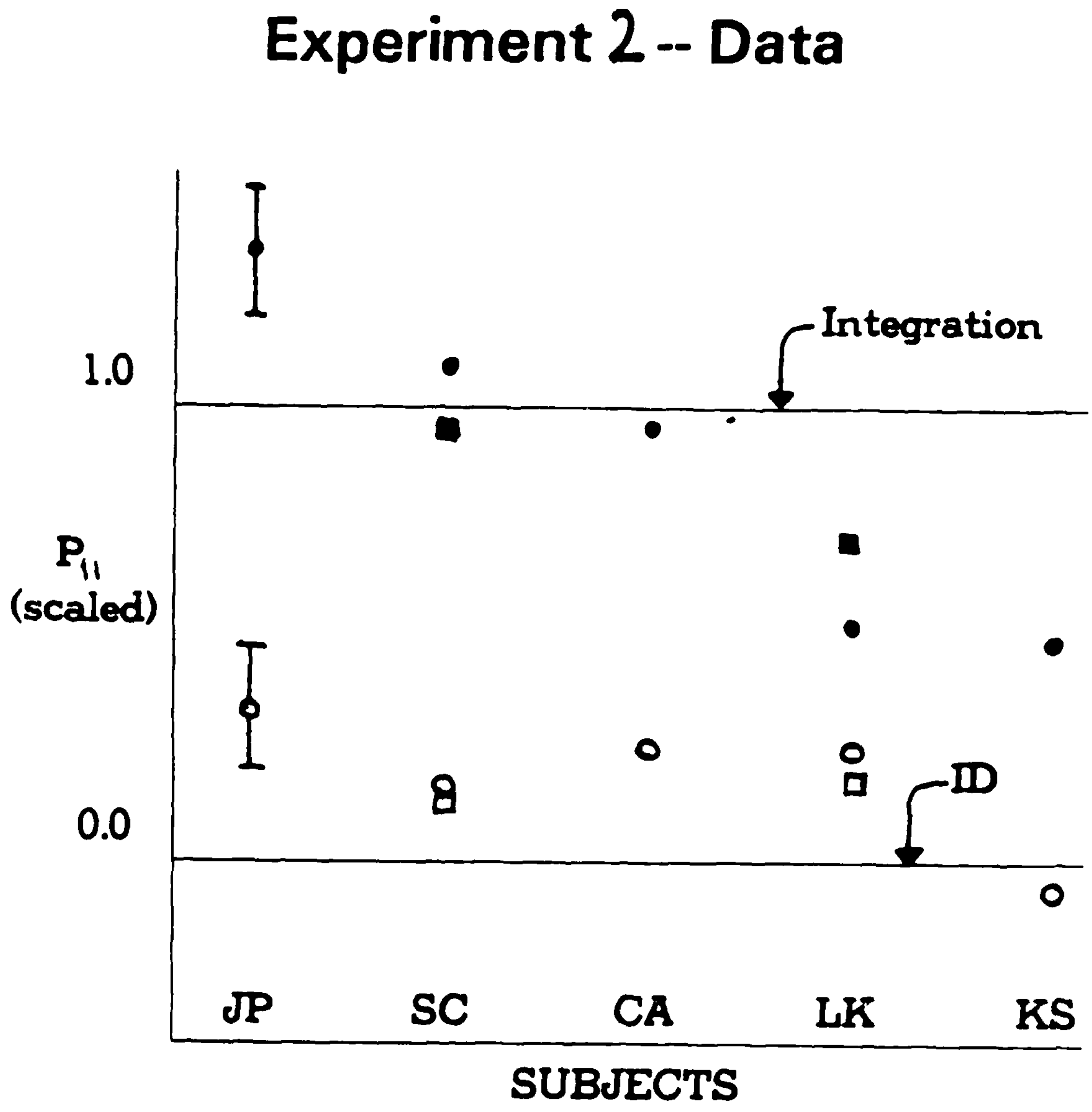

FIGURE 5. DATA FROM EXPERIMENT 2, FIRST REPLICATION (CIRCLES) AND SECOND REPLICATION (SQUARES).

Appendix 1

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INFORMATION INTEGRATION IN AUDITORY DETECTION

Robert M. Mulligan and Marilyn Shaw

Rutgers University
New Brunswick, N. J.

Bell Laboratories
Murray Hill, N. J.

In the experiments discussed below we investigated how people combine internal representations of pure tone signals in a detection task. On each trial, one of four possible stimuli is presented in a continuous background of broadband noise: Tone A, Tone B, Tones A and B (the complex tone), or just noise. The occurrence of either tone on a trial is statistically independent of the presence of the other tone.

We assume that processing of pure tones is mediated by a pitch coding mechanism consisting of a series of rather broadly tuned frequency filters. Our conception of these filters is based on the ``critical band'' (CB) notion derived from masking experiments by Fletcher (1940) and others. Fletcher first measured the threshold intensity of a pure tone signal centered in broadband noise. He then repeated this measurement several times with successively narrower noise bands while holding constant the spectral level of the noise (N_0). In doing so he was able to show that only the noise within a limited band was effective in masking the signal. Fletcher called this effective band of frequencies the <u>critical band</u> (CB). The implication of this phenomenon is that the energy from the tone and from that portion of the mask lying within a CB are summed, resulting in a lower signal-to-noise ratio. Energy from stimuli (noise or other tones) outside the CB has no influence on detectability of the signal tone.

In studies of this type, the bandwidth at which signal threshold is decreased by 3 dB relative to the wideband noise condition has been defined as the critical bandwidth (CBW) for that signal frequency, and is seen as representing the effective width of the internal frequency filter. Several experiments have estimated the critical band to be about 60 Hz wide at 1000 Hz and to gradually increase with increasing signal frequency.

Scharf (1970) and Zwicker, Flottorp and Stevens (1957) have reviewed results of a number of other studies which have used techniques other than masking to demonstrate CBW-like phenomena. These techniques, most often involving loudness summation or detection of phase differences, estimate CBWs which are 2 to 3 times wider than those arrived at in masking studies. Explanations for the differences in estimates of CBW have been offered elsewhere (Green, 1976; Swets, Green & Tanner, 1962). It seems likely that these various phenomena are manifestations of the same mechanism. This mechanism is most often modeled as a set of internal filters in the auditory system.

How then might the output of these frequency filters be applied in the case of a detection task? The notion of ``energy summation'' within a critical band led us to expect one pattern of detection results when the tones in a task were widely separated in pitch and another pattern, due to

energy summation, when the tones were in the same CB. These two ways of combining information about the component frequencies in a complex tone are depicted in Figure 1. In

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Insert Figure 1 About Here

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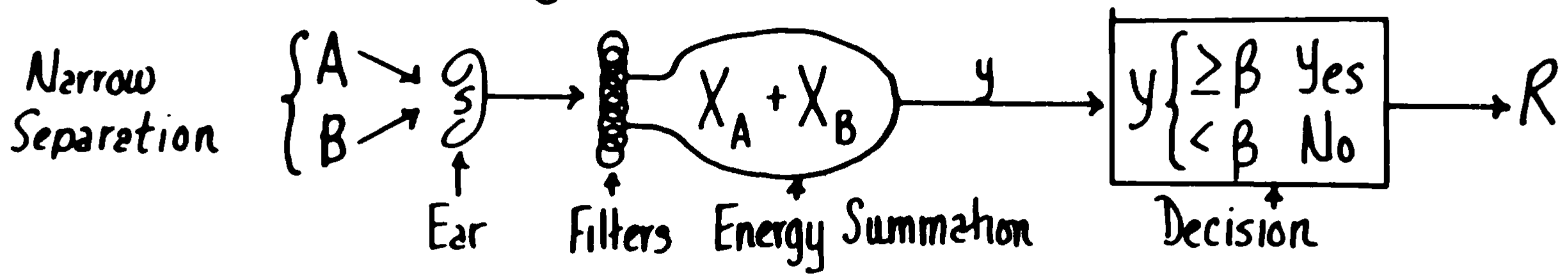
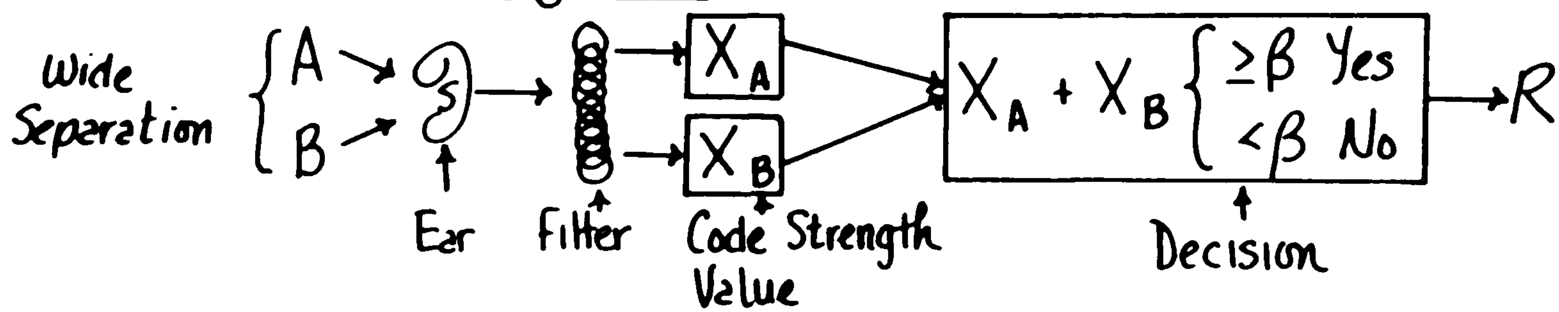
the upper diagram we have shown the case of energy summation within a frequency filter for two narrowly separated frequencies, which we will call <u>within-filter integration</u>. In the lower diagram we have schematized <u>across-filter integration</u> -- statistical summation at the outputs of separate filters. Here we are assuming that the filter output consists of a strength measure (X_A or X_B) which preserves rather fine-grained information regarding stimulus magnitude. For both types of integration, after summation takes place, the pooled information is then compared to a criterion, β. Based on this comparison, a ``yes-no'' response is formulated. When restated quantitatively, these two types of integration make different predictions about the extent to which detection performance should improve when signals are present at two different frequencies versus when only a single frequency is presented. Detailed discussion of these models can be found in Green and Swets (1974, Chapters 9 & 10). Leaving the quantitative predictions aside for the movement, the qualitative

Two Kinds of Integration

Within Filter Integration



Across Filter Integration

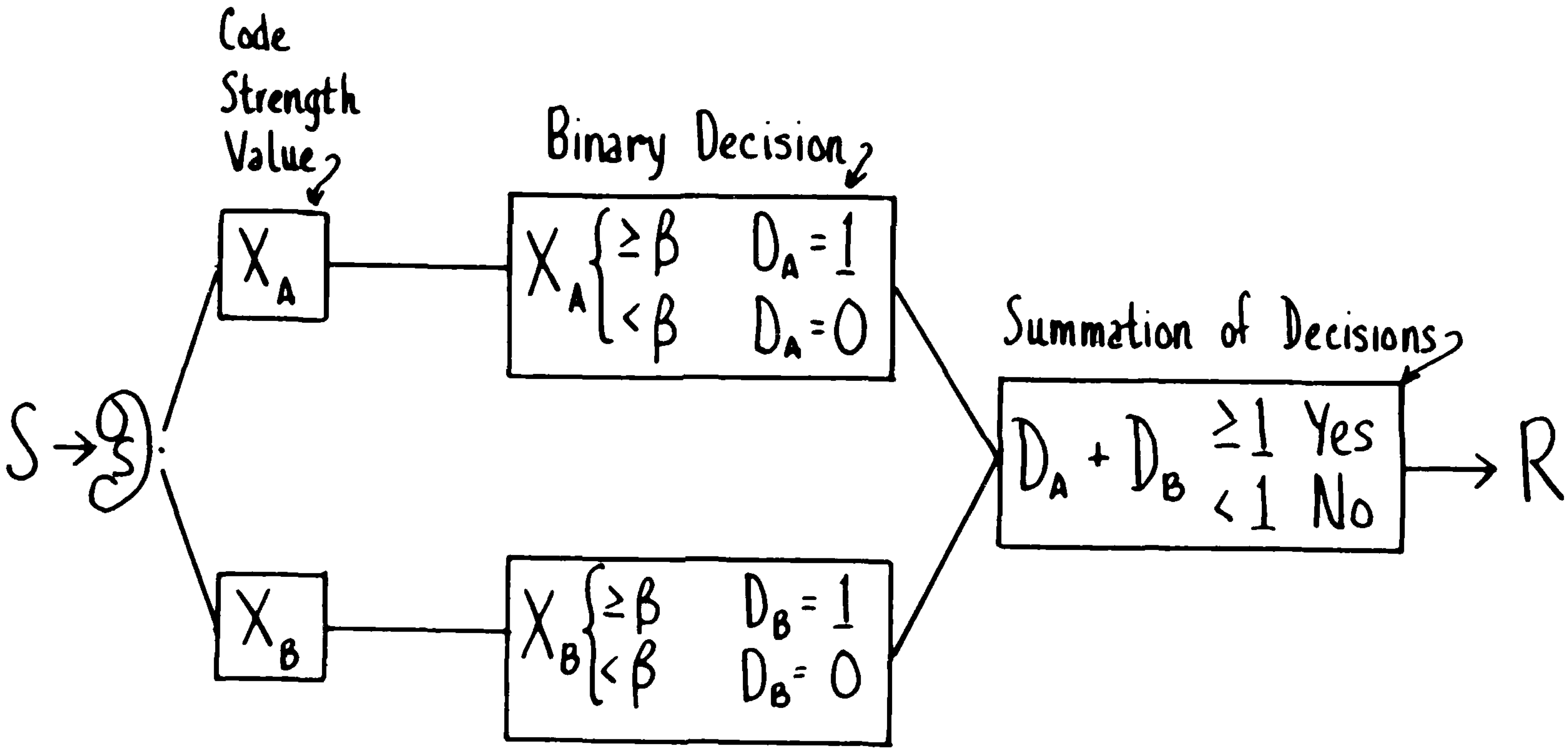


$$\boxed{Pr(\text{"No"}) = Pr(X_A + X_B < \beta)}$$

predictions call for a relatively larger gain in correct detections of the complex tone for within-filter than for across-filter integration. This predicted difference is based on the assumption that for across-filter integration, noise from two filters (2 CBWs) contributes to the signal-to-noise ratio, whereas for within-filter integration only one filter's noise contributes.

There is another type of explanation for how information about the components of a complex tone might be combined - the Independent Decisions Model. According to this model, separate ``tone present or absent'' decisions are made about the strength value associated with each tone in the complex. Within the framework of the frequency filters we have discussed, this type of decision process is plausible only when the component tones are far enough apart to fall in separate filters. The separate decisions are then accomplished by comparing the information available from each filter against its criterion, β_A or β_B. In a subsequent decision stage, as seen in Figure 2, the results of these binary categorizations are pooled to arrive at a response -- "yes" if the number of positive decisions exceeds a criterion, $\underline{c}$, and ``no" otherwise. In most studies, as in those to be reported here, subjects are instructed to say "yes" if <u>either</u> tone is detected.

Independent Decisions



$$Pr(\text{"No"}) = Pr(X_A < \beta)\, Pr(X_B < \beta)$$

To summarize, there are actually two questions to investigate: (1) how is information from separate frequencies combined (integration versus independent decisions), and (2) is there something special about pooling signals which are in the same CB (within-filter integration versus other models)? Though there are many studies of within-filter integration (Hall & Sondhi, 1977), there are a limited number of experiments with auditory stimuli have been directed at answering these questions together. These studies have been reviewed by Green and Swets (1974). With regard to the second question, our expectation of a within versus across-CB difference seems to be confirmed. Marill (1956) compared detection performance for pairs of tones within a CB (e.g., 500 and 540 Hz) and across CBs (500 and 1100 Hz). Data from the within-CB conditions reportedly (in Green & Swets, 1974) showed ``perfect energy summation'', the prediction of the within-filter integration model. Unfortunately there has been no published attempt to replicate this portion of Marill's experiment, and thus there is no other data from this type of simple two-tone detection paradigm where the component tones are clearly within a CB. Furthermore, since Marill's across-CB results are at odds with those from all other studies of this type (he reported no advantage for detection of his complex tone with widely separated components over single tone detection), there may be reason to suspect some

methodological peculiarity in his study. The experiments reported here attempt to clarify this question by looking at detection performance under a wide range of frequency separations.

Returning to the first of our two questions, a small number of tone detection experiments have compared the fit of Integration and Independent Decisions models (Schafer & Gales, 1949; Green, 1958; Green, McKay & Licklider, 1959). They were not successful, however, in discriminating between the two classes of models. The comparison is a difficult one because, under many circumstances the models make very similar predictions. In these early studies, for example, a threshold version of the of the independent decisions model (called Decision Threshold model) was usually tested in experiments where the number of frequencies subjects had to attend to varied between blocks of trials. The predictions of this model under these conditions, differ very little from those of the across-filter integration model.

Recently, however, Shaw (1982) has shown that it is possible to formulate these models in such a way that it becomes relatively easy to discriminate between Integration and Independent Decisions. She derived parameter-free predictions for each of the models in terms of the same response measure. Although this theoretical framework applies to any situation in which information from several

sources must be combined to arrive at a binary decision, we will describe the models and their predictions below in terms of the auditory stimuli of the current experiments. First, the two models must be restated formally. The general form of the Integration model is given in Eq. (1)

$$Pr(\text{"no"} \mid S_{ab}) = Pr(w_a X_a + w_b X_b < B) \tag{1}$$

where w_a and w_b weights associated with each strength value. We have chosen to state the model in terms of the probability of a "no" response because the predictions we will derive are more easily expressed in this form. After deriving the predictions, they can be restated in terms of probability of a "yes" response. Note that this model equation alone does not discriminate within- and across-filter integration. The continuous random variables X_a and X_b in the equation could represent either strength of some initial stimulus representation of two frequencies falling within the same CB, or the magnitudes of separate filter outputs. Later we will discuss the additional analyses required to discriminate these two possibilities.

The formula for the Independent Decisions model is given in Eq. (2). According to the model, the "no" probability for a given stimulus in our paradigm should equal the product of the separate probabilities that the strength value for each signal frequency fails to exceed its

criterion:

$$Pr(\text{"no"} \mid S_{ab}) = Pr(X_a < \beta_a)\,Pr(X_b < \beta_b) \qquad (2)$$

In addition to the threshold versions mentioned earlier, the Independent Decisions model has also been referred to as Probability Summation and as an Extreme Detector model.

To present these predictions, we must first introduce some further notation. Let P_{ab} represent the observed probability of a "no" response for a given stimulus condition S_{ab} in our two-signal paradigm. The value of each subscript is one if the tone is presented and zero if not. Thus, P_{11} denotes the observed "no" probability given that both Tone A and Tone B are presented. Similarly, P_{10}, P_{01}, and P_{00} denote the "no" probabilities when Tone A alone, Tone B alone, or neither tone is presented respectively.

By examining the model equation for each of these four conditions, under various transformations of the response probabilities, simple additive relationships are obtained for predicting P_{11} from the other three response probabilities. For the Independent Decisions model we find that, after logarithmic transformation, the proportion of "no" responses in the "AB" condition can be predicted from the other three conditions as follows:

$$\ln P_{11} = \ln P_{10} + \ln P_{01} - \ln P_{00} \qquad (3)$$

To obtain the integration model prediction, it is necessary to transform the "no" probabilities into corresponding standard normal deviates or z-scores by the inverse Gaussian transformation. A parallel predictive equation is then obtained in terms of the z-scores.

$$z_{11} = z_{10} + z_{01} - z_{00} \tag{4}$$

A more detailed discussion of these models and derivation of their predictions is given in Shaw (1982).

Let us look at the possible outcomes of a multiple tone detection task with both small and large frequency separations. The implications of finding a particular model fit for the two classes of frequency separation are pointed out in Table 1.

Insert Table 1 About Here

Consider first pairs of tones within the same CB. Previous data would lead us to expect that the Integration model would fit better than the Independent Decisions. Furthermore, we expect a doubling of d', reflecting perfect energy summation within a filter. If the Integration model held, but d' of the complex increased by a factor of $\sqrt{2}$, it would indicate that strength values from separate filters

TABLE 1

Tone Separation	Model Fit	Type of Integration
Small-within C.B.	Integration + 2d′	Within Filter
	Integration + $\sqrt{2}$d′	Across Filter ⇒ narrower filters
	Independent Decisions	Combine Decisions ⇒ narrower filters
Large-Separate C.B.s	Integration + 2d′	Within Filter ⇒ wider filters
	Integration + $\sqrt{2}$d′	Across Filter
	Independent Decisions	Combine Decisions

were being summed. In this case, we would conclude that the widths of these filters are narrower than originally believed. If the Independent Decisions model is supported we would conclude that frequency filters are more narrowly tuned than some models of critical bands would have us believe.

At large frequency separations the Integration model with $\sqrt{2}\,d'$ gain and the Independent Decision model seem equally plausible. With the first, a linear combination of strength measures across filters is implied. The latter implies that separate decisions about filter outputs are pooled. It is also possible, although not expected, that we would see integration with a doubling of d' for the complex tone. This result would imply that filters must be <u>larger</u> than expected.

Why should the Independent Decisions model fit our data? One reason is based on considerations of optimality. In the earlier auditory studies, there was no trial-to-trial uncertainty about how many tones would be presented. Tone A, Tone B, and the A-B complex tone were presented in separate blocks. Under these conditions, it has been shown that the Integration rule leads to optimal performance with the complex tone. But, in our experiments, there <u>is</u> uncertainty. Different stimuli are mixed within a block of trials so subjects do not know whether Tone A, B, or the

complex will be presented. Under these conditions, we have shown that Independent Decisions is nearly optimal.

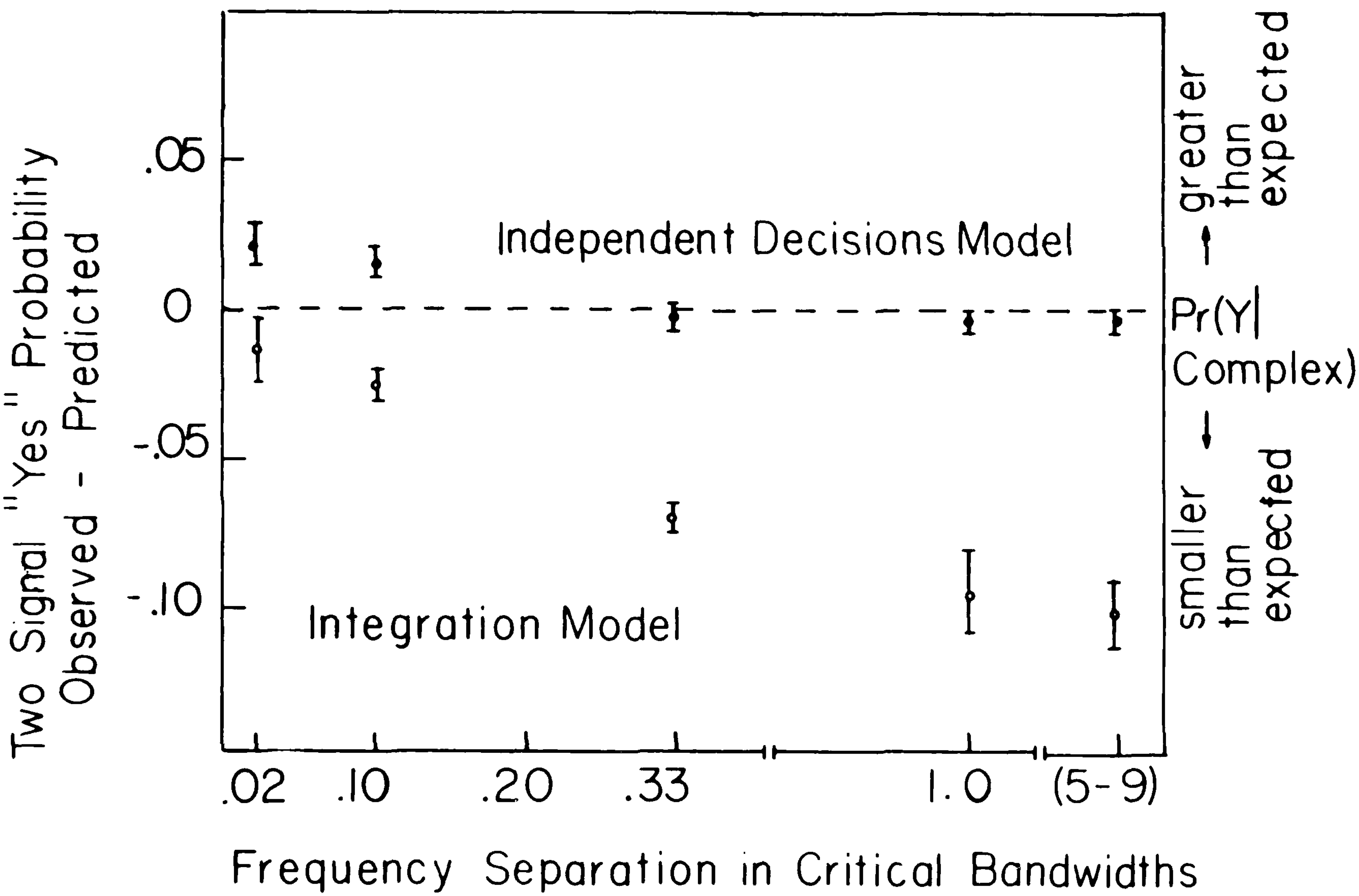
There is also some empirical support for the Independent Decisions model. Green, Weber, and Duncan (--) found evidence for Independent Decisions with tones separated by about one CB or greater. The model has also been supported in several of our previous studies using visual and bimodal stimuli (Mulligan & Shaw, 1980; Shaw, 1982).

Method

We carried out three experiments. The range of frequencies used was 470-3260 Hz, and the pairs of tones within a block of trials differed in frequency by from 0.02 to about 10 critical bandwidths. We used Zwislocki's (1965) empirically derived equations for calculating critical bandwidth.

Insert Figure 3 About Here

The data are shown in Fig. 3. For each of the models, we have plotted the predicted probability of a "yes" response to the complex tone minus its observed value as a function of critical bandwidth. The data are averaged across 7



Two Signal "Yes" Probability
Observed - Predicted
.05
0
-.05
-.10
Independent Decisions Model
Integration Model
greater than expected
Pr(Y| Complex)
smaller than expected
.02
.10
.20
.33
1.0
(5-9)
Frequency Separation in Critical Bandwidths

subjects and across different tone pairs having the same CBW separation. The vertical bars indicate the standard error about each point. Where the points lie below the ``zero difference line'', the observed proportion of "yes" responses for the complex stimulus falls short of that predicted by the model. Points lying above the zero difference line indicate that subjects response "yes" to the complex stimulus more often that predicted by the model.

It is clear that the Independent Decision model provides a better fit when stimulus frequencies were separated by one or more CB's. Here are the data for tones within the same critical band. The results are clear for 33 percent of a critical bandwidth - the Independent Decisions model does well - clearly better than the Integration model. But notice what happens as the frequencies of the tones get closer together -- at 10 and 2 percent CBW separation. The proportion of "yes" responses to the composite stimulus becomes larger than that predicted by the Independent Decisions Model, and much nearer to the prediction of the Integration model. When we look at individual subject's data at the 2% separation, every subject's data fits the integration model better than the Independent Decisions model. Furthermore, the data departs significantly from the Independent Decision model.

We can now ask whether integration at the 2% CBW is within filter or between filter. Unfortunately, the answer is ambiguous. d' for the complex tone was too small to confirm within filter integration and too large to be consistent with across filter integration. Now let us turn to the 10% separation. Here, both models are rejected.

To summarize then, we find clear support for Independent Decisions for tones separated by 33% of a critical band or more, and evidence for Integration of the component signals when they are separated by 2% of a critical band.

What can we conclude from our studies? We started out expecting to find evidence for Independent Decisions with frequencies separated by several critical bandwidths and evidence for Integration with frequencies in the same critical band. At the extremes of frequencies separation our expectation was confirmed. The surprise was the finding that independent decisions holds for tones separated by only about one third of a critical bandwidth. This suggests that independent pitch codes are possible at much narrower frequency separations than suggested by masking studies.

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